

Beyond spot diagrams: End-user oriented optical design

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Abstract: In this talk, two examples are given of the process of translating user requirements into optimization and assessment tools. In the first place, recent work on the effects of aberrations on the perceived image quality of visual instruments is reviewed. This allows the assessment of a visual system in terms of expected loss of contrast and resolution as a function of aberration, and also the formulation of an image quality metric suitable for automatic optimization. The second example concerns the extraction of accurate spectroscopic information from pushbroom imaging spectrometers. It is shown how the user requirements for calibration translate into spectral and spatial uniformity of response, and further to the complete absence of spectral and spatial distortion, as well as to the minimization of the variation of the LSF width in both directions, spatial and spectral. Techniques for accomplishing this in practice, both in terms of merit function and in terms of fabrication and assembly, are also discussed.

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1. Introduction

There is, by now, a wealth of starting designs available in the literature to satisfy almost any conceivable requirement. With the addition of the powerful software that is now in wide use, optical designers have a formidable arsenal at their disposal. With the help of global optimization routines, one can now concoct solutions that would have needed a lot more knowledge and imagination in the past, or one can extract the last ounce of performance from a given design form. Yet, while it may seem that much of the creative aspect of optical design has been surrendered to the mind-numbing, number crunching machine, there is still an area of research that promises to be fruitful for a while to come. That area is the proper understanding of user requirements and their translation into optimization operands or design assessment tools. This ultimately means that the designer must understand more than just ray tracing, and be able to extend into other disciplines as needed. One often finds that end users do not have a complete understanding of their own requirements, and that an exchange with a knowledgeable designer can help both sides to specify the problem properly. Two examples of this process are provided below: visual instrumentation, and imaging spectrometry.

2. Assessment of the image quality of visual instrumentation

There is a dearth of psychophysical studies on the perceived image quality of visual instrumentation. The effects that have not been thoroughly investigated outnumber those that have. The situation is complicated by the difficulty of performing such experiments, with the result that a single psychophysical study of a particular effect is rarely adequate, and any two studies rarely come to the same conclusion. But at least one area, the examination of the effects of primary aberrations, has benefited from a number of relatively recent studies.¹ The results from these studies can be used in two ways: in raw form, as a means of assessing the net resolution or contrast loss for a given amount of aberration, or by seeking an image quality metric that can summarize them and that can be turned into a form suitable for automatic optimization.

Use of the raw data can be useful but it is limited because one cannot readily estimate the effect of arbitrary aberration combinations from data on individual aberrations. The image quality metric that emerged from these studies is a limited integral of the MTF, extending from 5 to 20 c/deg in the eye space, which has been shown to correlate well with available data sets. This integral is best thought of as a volume, that is, over all azimuths in which case it is then denoted as MTF_v, although specific conditions of use may permit simplification to only two dimensions (MTF_a).

All image quality metrics are strongly focus-dependent, so the most critical question that needs to be answered is at what focal plane to perform the computation of the metric. The best metric is that which

has a maximum or minimum at the same focal plane as the eye would choose through accommodation under the prevailing aberration conditions. In the case where the instrument aberrations are generally larger than those of the eye, the evidence presented points to the conclusion that for the purposes of optimization and testing and at pupil diameters ≤ 3 mm, the eye can be simplified as a diffraction-limited focusing mechanism that chooses the focus by maximizing the MTF_v (or MTF_a). This also allows competing designs to be compared in terms of their effect on the MTF_v.

A recommended optimization method has been developed. According to the method, one first obtains a preliminary design using a rapid means of assessment based on geometric optics or spot diagrams, which is advantageous because MTF computations can slow down the optimization considerably. One then constructs the MTF-based merit function for final design optimization. In so doing, one can also set limits for the maximum allowed field curvature by letting the image surface to curve within certain limits, as well as chromatic aberrations and distortion. The preferred focus setting must also be set for the middle of the field. Chromatic aberrations are included separately since the MTF_v and MTF_a are monochromatic metrics, and no benefit has been demonstrated by the use of the polychromatic MTF under the conditions described. During optimization, the MTF_v computation can be simplified by computing the MTF at only a few frequencies and a couple of azimuths.

An example of applying this procedure demonstrated substantial improvement in image quality with the second round of MTF optimization, beyond the optimum spot diagram solution. In other cases it was possible to obtain a similar solution by simply switching to a wavefront-based merit function. However, the importance of the present procedure is that it provides an assurance that the best possible design has been obtained, based on solid psychophysical experiments about expected observer resolution and contrast sensitivity performance.

Two further examples are given, involving the performance assessment of a highly corrected Keplerian-type telescope, and of an inexpensive Galilean-type magnifier. It is shown how one can predict the anticipated performance from the available data.

It should be clear that the requirements for visual instrumentation are not exhausted by the above considerations. Indeed in many cases, small amounts of aberration are entirely secondary to other effects such as binocular disparity, or display resolution for electro-optical display systems. It is up to the designer to understand these effects and provide a design tailored to the circumstances.

3. Spectroscopic data fidelity of pushbroom imaging spectrometers

Pushbroom imaging spectrometers, in which the image of a slit is dispersed and imaged on an area array, suffer from potential artifacts relating to the lack of perfect registration between aerial image and detector, as well as the variation of the PSF characteristics in the spatial and spectral directions. The impact of those effects on sensor data fidelity has only recently been fully appreciated.^{2,3}

This is a classic case where the instinct of the designer as well as the tendency of automatic optimization routines to reduce spot size need to be tempered by an understanding of the application requirements. Accurate spectral information can be more crucial than high spatial resolution. This is because the existence of a target can be inferred from its spectral signature, even if it is not spatially resolved. Thus it may be advantageous to increase the amount of aberration in the system, if doing so will result in other desirable characteristics.

As a result of these considerations, two more requirements were added to the original user requirement for lack of distortion which would enable proper spectrum registration. Those were the constancy of the spectral response function with field, and the constancy of the spatial response function with wavelength. The spectral response function is defined as the convolution of the spectral LSF with the slit, the grating, and the detector response functions. The spatial response function is the convolution of the complete system spatial LSF with the detector response function. Assuming an ideal detector, that is, one with constant pixel response characteristics, those additional requirements translate into constancy of the LSF along the spectral and spatial directions. Since diffraction spread can be very different from one end of the spectrum to the other (typically a factor of 2.5), this means that the short wavelength LSF must be degraded by some amount to match that of the longer wavelength.

To accomplish these ends, an MTF-based optimization procedure was developed that relies on equalizing the MTF through field or wavelength as needed at the Nyquist and twice Nyquist spatial frequencies, in addition to controlling distortion at the submicron level through the chief ray or centroid coordinates. The process was tested at first on spectrometer systems that could not be characterized as very

demanding in terms of the field and dispersion characteristics – it was only the response uniformity requirements that made them extraordinary. Such systems tend to have a slit height of ~ 15 mm and a spectral sampling of ~ 10 nm. The merit function performed very well, producing systems with almost zero undesired variation. A more demanding case was a slit of 54 mm, and a stated user requirement of no more than 10% total spectral nonuniformity. Despite the tremendous size of the slit, the optimization method was still able to produce the desired result by adjusting only the weighting factors. Figure 1 shows the spectral response function variation for the first pass design in which only the distortion was corrected, and the same case with the full merit function.

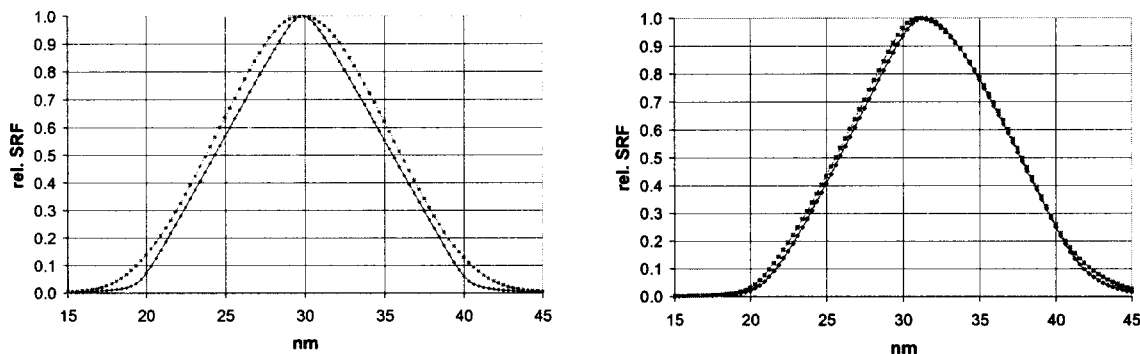


Fig. 1: Maximum variation in the spectral response function of an imaging spectrometer system with a 54 mm slit, optimized for lack of distortion only (left), or for spectral and spatial response uniformity (right). The slight asymmetry in the response to the right is due to the deliberate introduction of coma in the design. The increased uniformity comes at a small cost in MTF or ensquared energy: 91% instead of 95%.

Further work was performed in order to realize these small nonuniformity values in practice. This resulted in the development of alignment and tolerancing methods that inform and constrain the design process.⁴ Thus, for example, if the same spatial information is shared spectrally by two different spectrometer modules, then fabrication and alignment techniques need to be developed that would allow the two modules to have the same magnification within a small fraction of pixel size. Concentric spectrometer forms⁵ are advantageous in this respect because of their inherent lack of distortion as well as utilization of all spherical surfaces that can be manufactured to high accuracy.

One final piece of the puzzle is the proper modeling of the grating in those cases where it has more than one panel or blaze area in order to cover a broad band. In such cases, it is necessary to take both apodization and possible dephasing between panels into account, and both these effects are unfortunately wavelength-dependent. The detailed modeling can be so complicated that it cannot be usefully employed during optimization but only later, during assessment of the results.

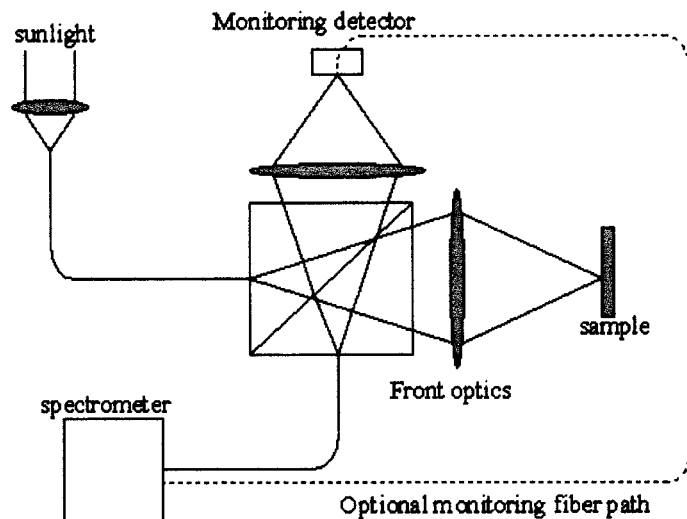
Section 3 of the research described here has been performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

4. References

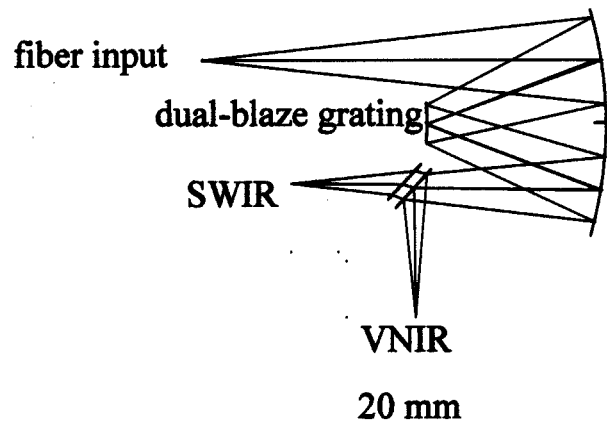
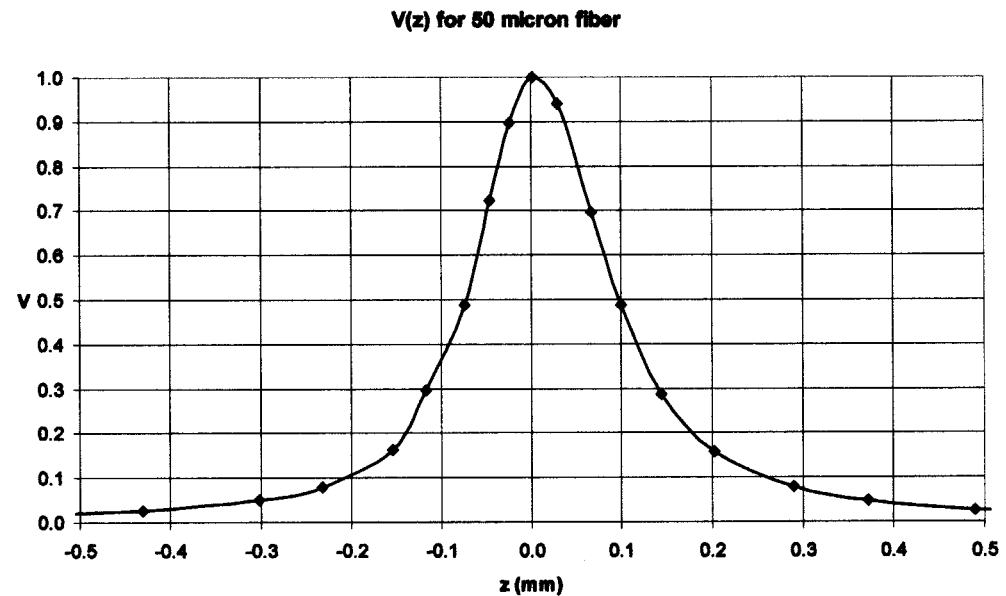
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Confocal, multimode fiber reflectance microspectrometer

Schematic



autofocus/vertical resolution



Miniature reflectance spectrometer

- 400-2500 nm
- 280-2500 nm option
- 10 nm sampling

